THE ASTROPHYSICAL JOURNAL, 392:706–709, 1992 June 20

UPPER LIMIT TO THE MASS OF PULSATIONALLY STABLE STARS WITH UNIFORM CHEMICAL COMPOSITION

RICHARD B. STOTHERS
Institute for Space Studies, NASA/Goddard Space Flight Center, 2880 Broadway, New York, NY 10025
Received 1991 October 21; accepted 1991 December 26

ABSTRACT

Nuclear-energized pulsational instability is a well-known feature of models of chemically homogeneous stars above a critical mass. With the new Rogers-Iglesias opacities, the instability occurs above 120–150 $M_\odot$ for normal Galactic Population I chemical compositions, and above $\sim$90 $M_\odot$ for stars in metal-poor environments like the outer Galaxy and the Small Magellanic Cloud. Models of homogeneous helium-burning stars are unstable above masses of 19 and 14 $M_\odot$, respectively. These significant increases of the critical masses, in the normal metallicity cases, over the values derived previously with the Los Alamos opacities can explain the stability of the brightest observed O-type stars, but they do not exclude the possibility that the most luminous hydrogen-deficient Wolf-Rayet stars are experiencing this type of instability.

Subject headings: stars: early-type — stars: fundamental parameters — stars: interiors — stars: oscillations — stars: Wolf-Rayet

1. INTRODUCTION

Theoretical models of chemically homogeneous stars are unstable toward nuclear-energized pulsations above a critical mass (Ledoux 1941). Instability arises only in the fundamental mode of radial pulsation because only this mode provides large pulsational amplitudes near the stellar center as a result of the high radiation pressure and low central condensation that prevail in very massive stars. Nearly all of the pulsational damping, however, occurs not far below the surface and can be very sensitive to the radiative opacity there.

For a simple Thomson electron-scattering opacity, the maximum stable mass of Population I stars is $\sim$60 $M_\odot$ (Schwarzschild & Härm 1959; Boury, Gabriel, & Ledoux 1964). The inclusion of atomic absorption in the total opacity raises the upper mass limit by increasing the central condensation of the star as well as the positive dissipation of pulsation energy in the envelope. With the use of a combination of Thomson electron-scattering opacity and Kramers's law of opacity fitted to the old Argonne opacity tables (Keller & Meyerott 1955), the increase of the critical mass is very small (Talbot 1971; Sastri & Stothers 1974; Aizenman, Hansen, & Ross 1975). On the other hand, various versions of the Los Alamos opacities (Cox & Stewart 1965, 1970; Cox & Tabor 1976) lead to a critical mass of 80–100 $M_\odot$ (Stothers & Simon 1970, Paper I; Ziebarth 1970; Papaloizou 1973; Maeder 1985; Cahn, Cox, & Ostlie 1987; Odell et al. 1987). These results cast some doubt on the large value of 440 $M_\odot$ that was derived by Klapp, Langer, & Fricke (1987), also using Los Alamos opacities.

Pure helium stars become pulsationally unstable above a mass of 7–8 $M_\odot$ for a simple Thomson electron-scattering opacity (Boury & Ledoux 1965) or above 9.2 $M_\odot$ when the Compton correction is included (Noels 1967). Both the Los Alamos and Carson (1976) helium opacities yield a critical mass in the range 11.5–13 $M_\odot$ (Paper I; Stothers 1976; Noels & Masereel 1982). With the addition of 2% metals by mass, the critical mass rises to 15–16 $M_\odot$ in the case of the Los Alamos opacities (Paper I; Noels & Masereel 1982). Critical masses based on Carson's metal opacities (Stothers 1976) will be ignored here because the metals contribution to the opacities was in part incorrectly calculated (Carson et al. 1984).

A larger critical mass can be obtained by further increases of the atomic absorption near the stellar surface (Sastri & Stothers 1974). New atomic opacities produced at Livermore (Iglesias & Rogers 1991; Rogers & Iglesias 1992) contain radiative contributions from many more metallic absorption lines than were included in the Los Alamos and Carson computations. These revised opacities are substantially enhanced at temperatures above 10^5 K. The purpose of the present paper is to determine how far the maximum mass of stable stars with a homogeneous chemical composition is raised by using the new Rogers-Iglesias opacities and to discuss the observational implications of the results.

2. ASSUMPTIONS AND METHODS

The opacity tables of Rogers & Iglesias (1992) need to be extrapolated to slightly lower densities at some temperatures in order to calculate the present stellar models. The extrapolation has been done by noting that the tables contain values of the opacity at semidecadal intervals of density and that, one decade beyond the tables' limit, electron scattering is expected to dominate the total opacity. Cox & Stewart's (1965) standard opacities in the formulation used in Paper I were therefore adopted for all extrapolated grid points, with probably little error. Linear interpolation between all grid points was done in the logarithms of density, temperature, and opacity. Tests show that the use of linear interpolation leads to a typical error of less than 7% in the derived critical masses.

Other assumptions are the same as in Paper I, except for the numerical method of solving the linearized pulsation equations in the nonadiabatic surface region. In Paper I a simple correction to the quasi-adiabatic approximation was adopted, whereas here an exact nonadiabatic calculation is performed, following a shooting method originally employed by Baker & Kippenhahn (1962) for Cepheid envelopes but modified so as (1) to allow a stable, continuous integration from the nonadiabatic outer layers into the quasi-adiabatic interior and (2) to allow a match between surface-inward and center-

TABLE 1

CRITICAL MODELS FOR THE HYDROGEN-BURNING MAIN SEQUENCE

	Z			
VARIABLE	0.03	0.02	0.004	0.002
$M/M_{\odot}$	148	121	89	84
q_f	0.84	0.82	0.79	0.78
β_c	0.45	0.49	0.56	0.58
$\log T_c$	7.63	7.63	7.66	7.68
$\log \rho_c$	0.08	0.16	0.35	0.42
$\rho_c/\langle\rho\rangle$	38	35	27	26
$\log (L/L_{\odot})$	6.36	6.24	5.99	5.95
$\log (R/R_{\odot})$	1.27	1.21	1.06	1.02
$\log T_e$	4.72	4.72	4.73	4.74
ω^2	3.1	3.2	3.1	3.1
Period (hr)	10.6	9.1	6.5	5.9

outward integrations for the solution of a complete star (see Stothers 1976). This numerical method is capable of achieving arbitrarily high resolution, although such a capability is not really necessary to obtain the period and simple eigenfunctions of the fundamental radial mode.

Other pulsation modes are already known to be stable at high stellar masses for chemically homogeneous models. These modes include the radial overtones (Simon & Stothers 1969b; Ziebarth 1970; Papaloizou 1973; Aizenman et al. 1975; Odell et al. 1987) and the p, f, and g^+ nonradial modes (Wan Fook Sun 1966; Aizenman et al. 1975; Odell et al. 1987).

3. CRITICAL MASSES

Four chemical compositions have been selected for the new hydrogen-burning models. Two of them refer to normal massive Population I stars in the Galaxy: $(Y, Z) = (0.28, 0.02)$ and $(0.27, 0.03)$; the other two refer to the young metal-poor populations of the outer Galaxy and the Small Magellanic Cloud: $(Y, Z) = (0.24, 0.002)$ and $(0.24, 0.004)$. As usual, Y and Z represent the helium and metals abundances by mass, respectively. For the Large Magellanic Cloud, Y is known to be 0.25, and although Z is uncertain, it also lies somewhere between the normal Galactic and Small Cloud values.

Critical masses and other data are presented in Table 1; the notation follows Paper I. For a solar metals abundance of $Z = 0.02$, the critical mass based on the new opacities is 121 $M_{\odot}$. This value should be regarded as a minimum for the general solar neighborhood, because it is known that the critical mass increases with a larger metals abundance (Paper I; Ziebarth 1970), axial rotation (Stothers 1974), and interior evolution (Schwarzschild & Härm 1959), although tangled magnetic fields seem to make very little difference (Stothers 1979).

Among these parameters, we here specifically consider the metals abundance. If Z is increased to 0.03, the critical mass rises to 148 $M_{\odot}$, but in an extreme low-metallicity environment like the outer Galaxy or the Small Magellanic Cloud, the critical mass falls to $\sim 90\ M_{\odot}$.

A homogeneous helium-burning star containing a solar or somewhat larger metals abundance becomes unstable if its mass exceeds 18–20 $M_{\odot}$. For a very metal-poor helium-burning star, the corresponding limit is 14 $M_{\odot}$. Details of the models for helium-burning stars with the critical masses are presented in Table 2.

Although the present critical masses for both hydrogen-burning and helium-burning stars with very low metallicities are not significantly larger than those based on the Cox-Stewart opacities (Paper I), the increase of the critical masses for normal metallicities is substantial. The physical reason is that the increased Livermore metal opacities raise the absorption part of the total opacity while leaving the scattering part constant. This change makes the total opacity more dependent on temperature and density (the absorption part is approximately proportional to $\rho T^{-3.5}$). Two consequences then follow: (1) the local effective polytropic index in the stellar envelope is increased, leading to a larger central condensation of the star and hence to smaller pulsation amplitudes near the center, where the nuclear energy sources are located; and (2) the pulsational damping in the stellar envelope is enhanced, for the reason that, when the gas heats up during compression, the opacity drops by an increased factor, leading to greater heat leakage. In order to overcome these stabilizing influences, it is necessary to raise the stellar mass. At a higher mass, radiation pressure becomes a larger fraction of the total pressure, so that the pulsational amplitudes near the center also become larger. In addition, densities are lower, so that the total opacity approaches more nearly the constant scattering limit and hence becomes a weaker damping agent. Then excitation by nuclear reactions near the center can overcome the damping in the rest of the star.

4. OBSERVATIONAL IMPLICATIONS

Observationally, it is unclear how high stellar masses actually reach. The highest mass so far measured from a binary star orbit is $\sim 50\ M_{\odot}$ (or perhaps higher) for the secondary of HD 47129 (Hutchings & Cowley 1976; Stickland 1987). Luminosities of the brightest O-type stars known in the Galaxy and the Magellanic Clouds suggest an upper mass limit of $\sim 120\ M_{\odot}$ (Garmany, Conti, & Chiosi 1982; Humphreys & McElroy 1984; Garmany, Conti, & Massey 1987; Fitzpatrick & Garmany 1990), but many of these stars are not clearly resolved, and their luminosities are subject to uncertainty about the bolometric corrections that were applied. However, mass estimates of 150–200 $M_{\odot}$ (Maeder 1980) are clearly too high. Targeted studies of a few of the brightest O stars in the Magellanic Clouds have resolved all of them into two or more components, with no component apparently exceeding $\sim 90\ M_{\odot}$ (Heydari-Malayeri, Magain, & Remy 1988, 1989; Heydari-Malayeri & Hutsemékers 1991a, b). This result is reminiscent of Sharpless's (1954) early success in resolving compact O-star clusters in the Galaxy. Our present theoretical finding of pulsa-

TABLE 2

CRITICAL MODELS FOR THE HELIUM-BURNING MAIN SEQUENCE

	Z			
VARIABLE	0.03	0.02	0.004	0.002
$M/M_{\odot}$	20.1	18.6	14.5	14.0
q_f	0.75	0.74	0.70	0.69
β_c	0.53	0.55	0.60	0.61
$\log T_c$	8.30	8.29	8.28	8.28
$\log \rho_c$	2.57	2.58	2.64	2.65
$\rho_c/\langle\rho\rangle$	36	34	28	27
$\log (L/L_{\odot})$	5.68	5.62	5.44	5.41
$\log (R/R_{\odot})$	0.15	0.12	0.04	0.03
$\log T_e$	5.11	5.11	5.10	5.10
ω^2	3.7	3.6	3.5	3.5
Period (hr)	0.54	0.52	0.45	0.44

tional stability for masses up to at least $\sim 90\ M_\odot$ can probably explain the lack of significant variability in the brightest O stars.

The extremely luminous starlike object R136a in the Large Magellanic Cloud was for a while suspected to be the most massive star known, with a proposed mass of $\sim 3000\ M_\odot$ (Feitzinger et al. 1980; Cassinelli, Mathis, & Savage 1981). Its expected pulsational properties were discussed theoretically by Ledoux, Noels, & Boury (1982). Recently, however, R136a has been resolved into at least eight stellar components (Weigelt & Baier 1985; Neri & Grewing 1988; Weigelt et al. 1991), of which the brightest, R136a1, may contain a mass of no more than $\sim 250\ M_\odot$ (Walborn 1984). If R136a1 is truly a single star, perhaps it is rotating fast enough to be pulsationally stable. On the other hand, R136a1 may be a multiple star, with all components having subcritical masses. Either interpretation could explain why the combined object R136 displays no significant light or radial-velocity variability (Moffat, Seggewiss, & Shara 1985).

The more enigmatic variable star η Carinae in the Galaxy generates a present-day luminosity of $\sim 6 \times 10^6\ L_\odot$. This is a fairly well determined value because the star's distance is known and its radiation is emitted largely at long wavelengths by a cool dusty circumstellar envelope (e.g., van Genderen & Thé 1984). The central core, although partially obscured, is not hidden and has been resolved into at least four components (Weigelt & Ebersberger 1986; Hofmann & Weigelt 1988), one of them being much brighter than the others. Davidson & Humphreys (1986) estimate that this bright component, designated A, emits a luminosity of $\sim 2 \times 10^6\ L_\odot$. In the past, it has been suspected that η Car may (or may not) contain a pulsationally unstable supermassive main-sequence star (Burbidge 1962; Talbot 1971; Hoyle, Solomon, & Woolf 1973). If η Car A is such a star, it would have to be essentially unevolved in order to avoid pulsational stabilization. Its luminosity would then imply a mass of $\sim 130\ M_\odot$. On the other hand, if the oblate shape of the dusty circumstellar envelope (the "homunculus") reflects fast rotation of the underlying star (Hester et al. 1991), this star should almost definitely be stable against pulsation (Stothers 1974). In any case, there is much observational evidence to suggest that η Car cannot be unevolved—specifically, its known very high rate of mass loss, its substantial helium abundance ($Y \approx 0.4$), and its large ratio of nitrogen to carbon plus oxygen, as derived from measurements of the surrounding ejecta (Davidson et al. 1986; Burgarella & Paresce 1991). If η Car A happens to be a slowly rotating, evolved, quasi-homogeneous star, it just might be pulsationally unstable, as discussed below for certain Wolf-Rayet stars; but this interpretation seems very contrived. Other explanations for the violent instability of η Car have been proposed, but they are beyond the scope of this paper (see the reviews of older work in Stothers & Chin 1983 and of newer work in Davidson 1989).

A more promising group of stars that may represent nuclear-energized pulsators consists of the most luminous WN subtypes among the Wolf-Rayet stars (Simon & Stothers 1970). Originally, it was thought that pulsationally induced shock waves could drive off matter at a very fast rate from the surface of a supermassive main-sequence star, which might then look like a WN star; if mass loss kept the star in a quasi-homogeneous state during its evolution, pulsational instability might persist because the critical mass for stability is smaller for a helium-enriched homogeneous star (Paper I). Maeder (1980) later proposed the same idea but applied it to the most massive O-type stars. In view of the significant increase of pulsational stability that is bestowed by the larger opacities used here, this idea seems to be no longer tenable. On the other hand, radiation-driven mass loss by itself may be sufficient eventually to bring a very massive stable O star into a pulsationally unstable, quasi-homogeneous state near the helium main sequence, where the star could acquire WN characteristics (Simon & Stothers 1969a; Noels & Gabriel 1981; Maeder 1985; Kirbiyik 1987; Cox & Cahn 1988; Schaller 1990). Mass exchange in a close binary system could possibly bring about the same result (Paczyński 1967). Since the critical mass for a helium star is only 14–19 $M_\odot$, the most luminous representatives of the hydrogen-deficient Wolf-Rayet stars remain the best potential candidates for this type of instability.

5. CONCLUSION

Homogeneous stellar models built with the new Rogers-Iglesias opacities become pulsationally unstable at significantly higher masses than models constructed with the Los Alamos opacities if the stellar metallicity is normal. Further opacity work will probably increase the total amount of atomic absorption by a small factor (Rogers & Iglesias 1992), and therefore the critical masses derived here may be slightly too small. However, any future changes are not expected to alter the present conclusions about the expected pulsational stability of O-type stars and the expected pulsational instability of some extreme WN stars. These predictions have in fact already stood the test of time.

It is a pleasure to thank Forrest J. Rogers and Carlos A. Iglesias for supplying the new tables of opacities that were the basis of the present study. Chao-wen Chin kindly assisted in setting up the tables for stellar applications.

REFERENCES

Aizenman, M. L., Hansen, C. J., & Ross, R. R. 1975, ApJ, 201, 387
Baker, N. H., & Kippenhahn, R. 1962, Z. Astrophys., 54, 114
Boury, A., Gabriel, M., & Ledoux, P. 1964, Ann. d'Astrophys., 27, 92
Boury, A., & Ledoux, P. 1965, Ann. d'Astrophys., 28, 353
Burbidge, G. R. 1962, ApJ, 136, 304
Burgarella, D., & Paresce, F. 1991, A&A, 241, 595
Cahn, J. H., Cox, A. N., & Ostlie, D. A. 1987, in Stellar Pulsation, ed. A. N. Cox, W. M. Sparks, & S. G. Starrfield (Berlin: Springer), 51
Carson, T. R. 1976, ARA&A, 14, 95
Carson, T. R., Huebner, W. F., Magee, N. H., Jr., & Merts, A. L. 1984, ApJ, 283, 466
Cassinelli, J. P., Mathis, J. S., & Savage, B. D. 1981, Science, 212, 1497
Cox, A. N., & Cahn, J. H. 1988, ApJ, 326, 804
Cox, A. N., & Stewart, J. N. 1965, ApJS, 11, 22
———. 1970, ApJS, 19, 243
Cox, A. N., & Tabor, J. E. 1976, ApJS, 31, 271
Davidson, K. 1989, in Physics of Luminous Blue Variables, ed. K. Davidson, A. F. J. Moffat, & H. J. G. L. M. Lamers (Dordrecht: Kluwer), 101
Davidson, K., Dufour, R. J., Walborn, N. R., & Gull, T. R. 1986, ApJ, 305, 867
Davidson, K., & Humphreys, R. M. 1986, A&A, 164, L7
Feitzinger, J. V., Schlosser, W., Schmidt-Kaler, T., & Winkler, C. 1980, A&A, 84, 50
Fitzpatrick, E. L., & Garmany, C. D. 1990, ApJ, 363, 119
Garmany, C. D., Conti, P. S., & Chiosi, C. 1982, ApJ, 263, 777
Garmany, C. D., Conti, P. S., & Massey, P. 1987, AJ, 93, 1070
Hester, J. J., Light, R. M., Westphal, J. A., Currie, D. G., Groth, E. J., Holtzman, J. A., Lauer, T. R., & O'Neil, E. J., Jr. 1991, AJ, 102, 654
Heydari-Malayeri, M., & Hutsemékers, D. 1991a, A&A, 243, 401
———. 1991b, A&A, 244, 64
Heydari-Malayeri, M., Magain, P., & Remy, M. 1988, A&A, 201, L41

Heydari-Malayeri, M., Magain, P., & Remy, M. 1989, A&A, 222, 41
Hofmann, K.-H., & Weigelt, G. 1988, A&A, 203, L21
Hoyle, F., Solomon, P. M., & Woolf, N. J. 1973, ApJ, 185, L89
Humphreys, R. M., & McElroy, D. B. 1984, ApJ, 284, 565
Hutchings, J. B., & Cowley, A. P. 1976, ApJ, 206, 490
Iglesias, C. A., & Rogers, F. J. 1991, ApJ, 371, L73
Keller, G., & Meyerott, R. E. 1955, ApJ, 122, 32
Kirbiyik, H. 1987, Ap&SS, 136, 321
Klapp, J., Langer, N., & Fricke, K. J. 1987, Rev. Mexicana Astron. Af., 14, 265
Ledoux, P. 1941, ApJ, 94, 537
Ledoux, P., Noels, A., & Boury, A. 1982, A&A, 108, 49
Maeder, A. 1980, A&A, 92, 101
———. 1985, A&A, 147, 300
Moffat, A. F. J., Seggewiss, W., & Shara, M. M. 1985, ApJ, 295, 109
Neri, R., & Grewing, M. 1988, A&A, 196, 338
Noels, A. 1967, Ann. d'Astrophys., 30, 349
Noels, A., & Gabriel, M. 1981, A&A, 101, 215
Noels, A., & Masereel, C. 1982, A&A, 105, 293
Odell, A. P., Pausenwein, A., Weiss, W. W., & Hajek, A. 1987, in Stellar Pulsation, ed. A. N. Cox, W. M. Sparks, & S. G. Starrfield (Berlin: Springer), 47
Paczyński, B. 1967, Acta Astron., 17, 355
Papaloizou, J. C. B. 1973, MNRAS, 162, 143
Rogers, F. J., & Iglesias, C. A. 1992, ApJS, in press
Sastri, V. K., & Stothers, R. B. 1974, ApJ, 193, 677
Schaller, G. 1990, in Confrontation between Stellar Pulsation and Evolution, ed. C. Cacciari & G. Clementini (San Francisco: Astronomical Society of the Pacific), 304
Schwarzschild, M., & Härm, R. 1959, ApJ, 129, 637
Sharpless, S. 1954, ApJ, 119, 334
Simon, N. R., & Stothers, R. B. 1969a, ApJ, 155, 247
———. 1969b, ApJ, 156, 377
———. 1970, A&A, 6, 183
Stickland, D. J. 1987, Observatory, 107, 68
Stothers, R. B. 1974, ApJ, 192, 145
———. 1976, ApJ, 204, 853
———. 1979, ApJ, 229, 1023
Stothers, R. B., & Chin, C.-w. 1983, ApJ, 264, 583
Stothers, R. B., & Simon, N. R. 1970, ApJ, 160, 1019 (Paper I)
Talbot, R. J., Jr. 1971, ApJ, 163, 17
van Genderen, A. M., & Thé, P. S. 1984, Space Sci. Rev., 39, 317
Walborn, N. R. 1984, in IAU Symp. 108, Structure and Evolution of the Magellanic Clouds, ed. S. van den Bergh & K. S. de Boer (Dordrecht: Reidel), 243
Wan Fook Sun. 1966, Ph.D. thesis, Australian National University
Weigelt, G., & Baier, G. 1985, A&A, 150, L18
Weigelt, G., & Ebersberger, J. 1986, A&A, 163, L5
Weigelt, G., et al. 1991, ApJ, 378, L21
Ziebarth, K. 1970, ApJ, 162, 947